The LSST as a Supernova Light Curve Builder

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ABSTRACT

The Large-aperture Synoptic Survey Telescope is an effective 6.5m telescope with a 7 square degree field of view; such an observatory would be an excellent facility at which to search for and follow-up moderate-redshift supernovae. In this note, we determine the redshift depths where the LSST can get high-quality supernova light curves and the relevant systematic errors involved.

1. The LSST

A potentially powerful ground-based instrument for a high-redshift supernova search and follow-up photometric program is the proposed Large Synoptic Survey Telescope (LSST) with an effective 6.5 m aperture telescope. The relevant parameters describing the telescope, observing strategy, and a hypothetical instrument suite similar to SNAP's are given in Table 1. Weather and seeing conditions at Paranal, Chile are assumed. For completeness we include a NIR camera although such an instrument is not baselined for the LSST.

2. LSST Light Curves

The LSST can be used by itself or in conjunction with other telescopes to build photometric light curves and colors of supernovae. In an experiment limited by systematic errors, the precision of cosmological parameter measurements depends on the size of the systematic per redshift bin and on the range of redshifts observed. We thus examine the potential depth of an LSST search and its observational constraints on systematic errors by looking at the deepest possible light-curve points: all-night observations (9 hours) of a single field. The light curve is sampled periodically from 4–8 days, depending on redshift. The time gap is presumably filled with color measurements and/or different fields to increase the total number of supernova followed.

The extreme observations considered here do not represent a practical nor optimal observation program. The exposure times and cadence of the scanning strategy strictly limit the solid-angle of sky searched and the number of filters available for observation. This observing strategy is at odds with the planned scanning strategy of the LSST which calls for frequent (~ 4 day) short (~ 20 sec) observations of the full visible sky. Indeed, a shallower search that covers a larger solid-angle may provide more interesting supernova science, other than filling the Hubble diagram at high redshift.

The quality of expected LSST light-curves is illustrated in Fig. 1 which shows simulated redshifted B and V-band light curves as a function of redshift. The degradation of these measurements as the observed light moves toward the NIR is apparent. Table 2 shows how well representative LSST light curves are fit to peak flux (f_{max} which is normalized to one), date of maximum light (t_{max}), stretch (s) , explosion date (t_{exp}), the plateau level and its slope, and color. From observation and theoretical models, these parameters are expected to be valuable in tracking subtle differences in the intrinsic luminosity of the supernovae (as described in "Multi-Color Light Curve Measurements" in this Yellow Book.)

The LSST will have particular trouble in providing an extinction correction; for the uncertainty in this to be 0.1 mag requires a color measurement to 0.024 mag. This is only possible at $z \leq 0.8$. If

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Table 1
LSST Telescope, Instrument, and Site Parameters

Property	Value
primary aperture size (m)	8.5
secondary aperture size (m)	5.47723
imager focal length (m)	10.52
spot diagram (arcsec)	0.22
Readout Noise of the optical detector (e/pix)	4
Dark current of the optical detector (e/min/pix)	0.08
pixel size of optical detector (μm)	10.5
QE of the optical detector (%)	~ 90
CCD diffusion (μm)	5
Readout Noise of the NIR detector (e/pix)	6
Dark current of the NIR detector (e/s/pix)	0.017
pixel size of NIR detector (μm)	18
QE of the NIR detector (%)	~ 60
NIR detector diffusion (μm)	4
RMS flatfielding error	1e-4
Throughput of the camera (%)	58
Flux in radius aperture (%)	93
max exposure for a single image (min)	15
cadence for exposures (days)	4 ($z < 0.4$),6 ($0.4 < z < 0.9$),8($z > 0.9$)
B-band exposure time (photometry) (hour)	9
V-band exposure time (photometry) (hour)	9
atmospheric absorption	CTIO conditions
cumulative seeing	VLT conditions
photometric/patchy/cloudy (%)	78/87/96

the LSST is to provide rest-frame B-band light curves only, with NIR and spectroscopic observations sent to other larger aperture or space telescopes, the LSST data can probe slightly deeper redshifts. Stretch-correction errors of 0.1 mag require stretch measurement errors of 0.05 which are available only out to $z = 1$.

Of the more speculative indicators, the peak-to-tail ratio (or their magnitude difference) has a targeted binsize of 0.08 mag for subsample studies. The error in the plateau must be better than 0.08 which is not obtained for $z \geq 0.6$; the LSST will not be able to measure sufficiently accurately this potentially important parameter. The targeted bin size for the date of explosion is 0.2 days, a precision that is not obtained for $z \geq 0.6$ supernovae.

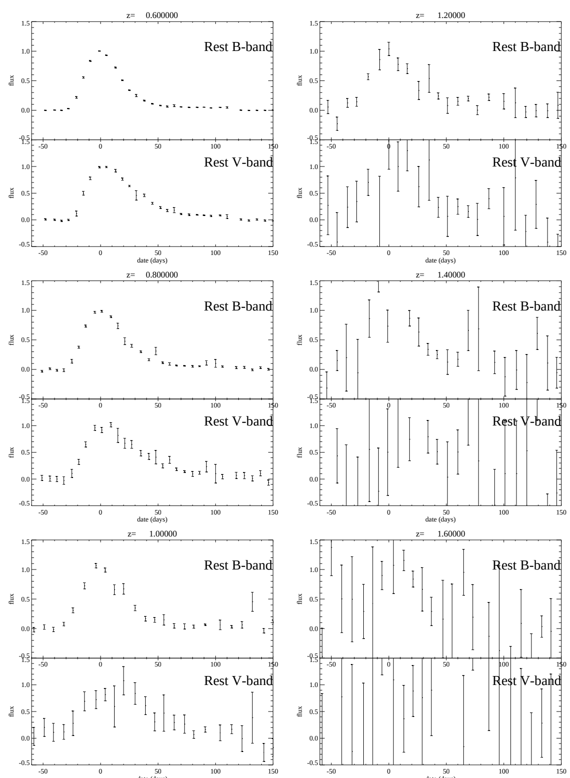

Fig. 1.— Simulated rest-frame B and V-band light curves from the LSST for a sequence of redshifts. The total integration time is 9 hours for each filter. Qualitatively, the color measurement degrades sharply at $z = 1.0$ while the B-band light curve fit degrades significantly at higher redshifts.

Beyond $z = 1.2$ the photometric errors are so large that no meaningful fit is obtained. Results on a less constrained fit using only the B band and fixing the plateau slope are shown in Table 3. In this case, lightcurves can be fit up to $z = 1.6$ although the uncertainties on the parameters can be terrible. Effectively no improvement is made on the measurement of stretch and the date of explosion, since the models for the plateau and the rest of the light curve are decoupled. As expected the plateau measurement does improve appreciably.

3. Malmquist Bias Measurement

Another systematic effect in a flux-limited survey is Malmquist bias where intrinsically brighter objects will be preferentially discovered. Simulated light curves of supernovae drawn at random redshifts, stretches, and magnitude (within the 0.1 mag SN Ia intrinsic dispersion) were generated and fit. Each redshift's observations are done with the corresponding redshifted B-filter. The detection threshold is set at 7σ, a realistic cut for an automated search. The results are shown in Figure 2.

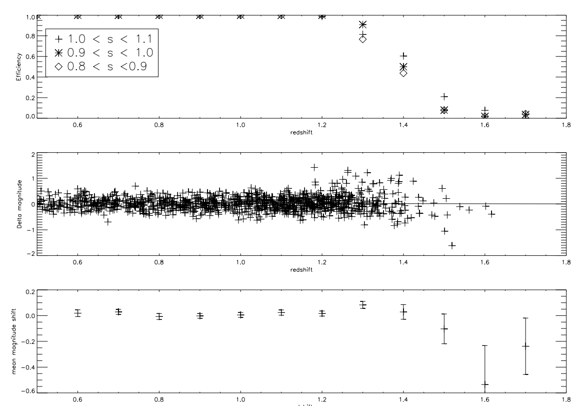

Fig. 2.— A study in Malmquist bias for an LSST search. The first figure shows the detection efficiency as a function of redshift for different stretch bins. The second shows the difference between the fit stretch-corrected peak magnitude and the "true" $s = 1$ peak magnitude. The third plot shows the same the average shift as a function of redshift bin.

The first plot shows the detection efficiency as a function of redshift for different stretch bins. Such a search will be complete through $z = 1.2$

TABLE 2
STATISTICAL ERRORS ON FIT PARAMETERS FOR LSST (ALL PARAMETERS FIT TOGETHER)

z	f_{max}	t_{max}	s	t_{exp}	plateau	plateau slope	color
0.6	0.003	0.06	0.006	0.28	0.093	0.002	0.009
0.8	0.009	0.12	0.014	1.22	0.28	0.007	0.027
1.0	0.024	0.35	0.040	1.35	0.66	0.013	0.103
1.2	0.076	0.58	0.112	1.51	0.93	0.027	0.23

TABLE 3
STATISTICAL ERRORS ON FIT PARAMETERS FOR LSST (SINGLE FILTER NO PLATEAU SLOPE)

z	f_{max}	t_{max}	s	t_{exp}	plateau	plateau slope	color
0.6	0.003	0.06	0.006	0.27	0.031	-	-
0.8	0.010	0.13	0.015	1.22	0.07	-	-
1.0	0.025	0.35	0.042	1.35	0.22	-	-
1.2	0.074	0.61	0.11	1.5	0.23	-	-
1.4	0.108	1.19	0.16	5.16	2.34	-	-
1.6	0.152	1.59	0.54	20.7	52.	-	-

and start to loose efficiency beyond. The second shows the difference between the fit stretch-corrected peak magnitude and the "true" $s = 1$ peak magnitude. The third plot shows the average shift as a function of redshift bin. As completeness is lost, for $z > 1.4$, a shift on the order of a few tenths of magnitude due to Malmquist bias already occurs. But this occurs only at a redshift larger than where we can precisely constrain the supernova light curve. More sophisticated trigger algorithms can also lower the signal-to-noise threshold further lessening the importance of this bias.

4. Conclusions

We find that an aggressively deep LSST supernova survey can provide good color and stretch measurements ($\sigma_m \sim 0.1$) out to $z \sim 0.8$ but cannot do well at higher redshifts. If the LSST is to provide only a B light curve, uncertainties in the s measurement for supernovae at $z > 1$ will propagate into stretch-correction errors larger than the intrinsic dispersion of supernovae.

The SNAP team has identified several light-curve observables that may be indicators of small (~ 0.02) magnitude heterogeneity within supernovae, beyond the light-curve shape correction. These observables are difficult to obtain, the LSST would not be able to obtain the desired precision on these features for supernovae beyond $z \geq 0.6$.

Malmquist bias has a significant effect at redshifts beyond where accurate light-curve fitting is possible. In other words, if you can get a good light-curve fit at a given redshift, Malmquist bias will not be a problem.

There are other systematic problems facing an LSST search not considered here. Logistically, a second large-aperture dedicated telescope would be required for NIR photometry, color measurements, and spectroscopy. It has been proposed that redshifts be obtained photometrically due to either the difficulty of getting spectra on high-redshift objects or the large numbers of supernovae that could be found in a ground search. As shown in "Redshift Errors and the Supernova Magnitude

Error Budget" in this Yellow Book, redshift errors such as those expected from photometric redshifts can have an appreciable effect on the magnitude error budget. It is also uncertain whether light curves in several filters can provide accurate supernova typing, leading to the risk of non-Type Ia's in an LSST sample.

In another note in this volume, we find that gray dust is not well constrained with only optical observations of supernovae out to $z = 1$.

The LSST can make an important contribution to supernova science with a shallower large solid-angle supernova search. The large number of supernova with supernova frame B and V light curves will provide large statistics with which to characterize Type Ia supernovae.

The analysis presented only shows the fit error of a single simulation realization. Future work will include a full Monte Carlo, however the basic results are not expected to change substantially.